Calculation the Translesional Pressure Gradients on Coronary Stenosis by Combining Three-dimensional Coronary Angiography Parameters with Frame Count Data

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Abstract

Background: Assessing the hemodynamic impact of an intermediate coronary artery stenosis on the basis of the diameter stenosis is often ambiguous. Measurement of the fractional flow reserve (FFR) is necessary in these cases for correct clinical decision making.

Aim: Determining the tranlesional pressure gradients, based on the data calculated from the 3D coronary angiography and the frame count method using classic fluid dynamic equations and to compare them with the measured values.

Methods: FFR measurements were performed on 15 coronary segments of 10 patients by PressureWire™ Certus. 3D reconstructions of the same segments were performed by the IC30 software (Siemens), and the cross-sectional area stenosis (AS) (%), the length of the lesion (L) (mm), the minimal lumen area (MLA) (mm2), the plaque volume (PV) (%) and the distal reference area (dRefA) (mm2) were determined. The flow velocity (mm/s) was assessed by the frame count on the coronary angiography following administration of 6 ml contrast material with a 3ml/s rate by ACIST™ Injection System (BBraun). Vessel length was determined on the 3D reconstruction. Pressure gradients (Hgmm) were calculated on the basis of the fluid dynamic equations:

dP= Q(Rp+QRt), where Rp= 0,75 x L / MLA^2

and Rt = 3,76x (1/MLA - 1/dRef A)^2,

Q(volumetric flow)(ml/s) = flow velocity x dRefA.

Results: Regression analysis has demonstrated significant relationship between the calculated and measured resting distal/proximal pressure ratio (r=0.66; p=0.007). Tight correlation has been found between the calculated and measured FFR (assuming twofold volumetric flow during vasodilatation) (r=0.88; p<0.001). Among the 3D parameters only the AS and the PV showed significant correlation with the FFR (r=0.62 and 0.71; p=0.013 and 0.003, respectively).

Conclusions: The calculation of pressure gradients by fluid dynamic equations using 3D coronary angiography and frame count data can predict the functional flow consequence of a stenosis.

1. Introduction

Maximal blood flow starts to decrease at 50% luminal diameter stenosis, but the resting flow is unaffected until there is more than 80% decrease. Should the pressure in the epicardial arteries increase or decrease, the pressure-flow curve keeps a linear or slightly positive slope: this is called autoregulation, while during maximal vasodilatation the pressure-flow relationship is approximately straight.

There are physical components to the flow changes (Figure 1). The equation that characterizes the severity of the stenosis is as follows:

$$\Delta P = fQ + sQ2$$

where ΔP is the pressure gradient, *f* is the frictional effect factor, *s* is the separation effect and *Q* is the flow. The pressure drop is a quadratic function of pressure loss due to viscous friction (f) and flow (Q) separation in the Poisseuille's law. The viscous friction pressure loss coefficient *f* is determined by the stenosis length (L) and inversely by the minimal cross-sectional lumen area (MLA): f ~ L / MLA2. The flow separation pressure loss coefficient *s* is influenced by the geometry of the stenosis (affected by the difference between the MLA and the non-stenotic part of the vessel: s ~ 1/ MLA^2 - AS^2/ MLA^{2}x104) and fluid properties of blood [1-3] .

In this study, our aim was to determine the translesional pressure gradient, based on the data calculated from the 3D coronary angiography and the frame count method using classic fluid dynamic equations.

2. Methods

2.1. Determining fractional flow reserve

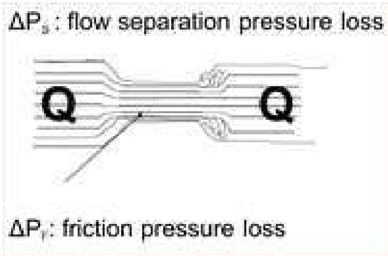

Figure 1. Pressure loss across the stenosis: as blood transverses a diseased arterial segment, friction and flow separation of laminar flow cause energy loss, resulting in a pressure gradient across the stenosis.

During cardiac catheterization through either femoral or radial artery, 6 F guiding catheter without side-holes was carefully positioned at the orifice of the left or right coronary artery to detect the proximal (aortic) pressure without damping. The distal pressure was recorded by pressure-sensor guidewire (PressureWire Certus, Radi Medical). First, the pressure trace from the semiconductor sensor at the catheter tip was equalized to the fluid fill pressure trace of the guiding catheter. Then the pressure wire sensor was advanced through the lesion to a distal position. 100 gamma nitroglycerine was administered to the guiding catheter to prevent arterial spasm. Maximal hyperemia was induced by intracoronary injection of 100 gamma adenosine, and **Pa** (aortic pressure at the guide tip) and distal coronary pressure (**Pd**, at the pressure sensor) were simultaneously measured. FFR was calculated as the ratio of these pressures: **Pa/Pd**.

At the end of FFR measurement the possibility of the drift of the trace was ruled out by pulling back the sensor to the tip of the guiding catheter (Figure 2.).

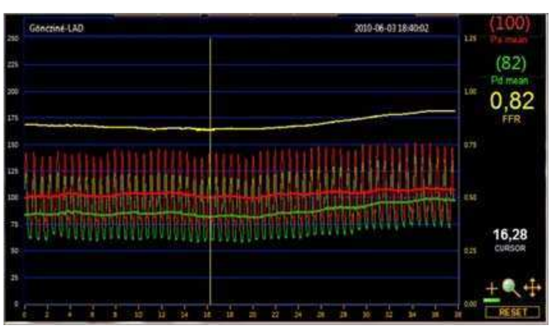

Figure 2. Result of FFR measurement of a representative case.

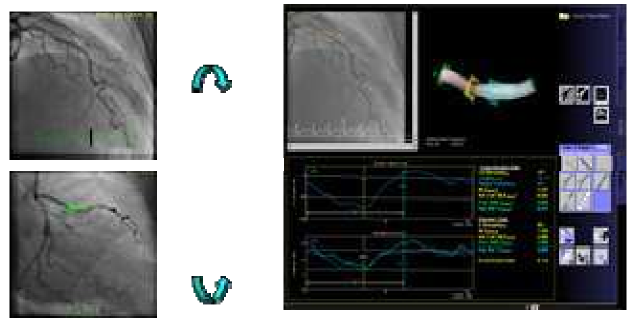

Figure 3. 3D reconstruction of a representative case.

2.2. 3D coronary angiography

IC30 software of the Axiom Artis (Siemens) X-ray machine was used to reconstruct a 3D model of a coronary artery by fusing two or more angiographic images. During conventional cardiac catheterization coronary angiographic cine images were acquired at 15 frames per second. 2 or 3 ECG-gated end-diastolic frames separated from each other by at least 30° were used to reconstruct the segment of interest at the coronary lesion. First the guiding catheter was used to calibrate pixel size.

The location of the stenosis, the proximal and distal coronary artery segments were manually identified on the images then the software automatically generated the arterial lumen in 3D (Figure 2). Cross-sectional area percentage stenosis (AS), plaque volume (PV) and minimum luminal area (MLA) were calculated by the program from 3D parameters.

2D quantitative analysis was also performed from the views depicting the most severe stenoses to calculate the minimum luminal diameter (MLD) and the percentage diameter stenosis (DS) (figure 3.).

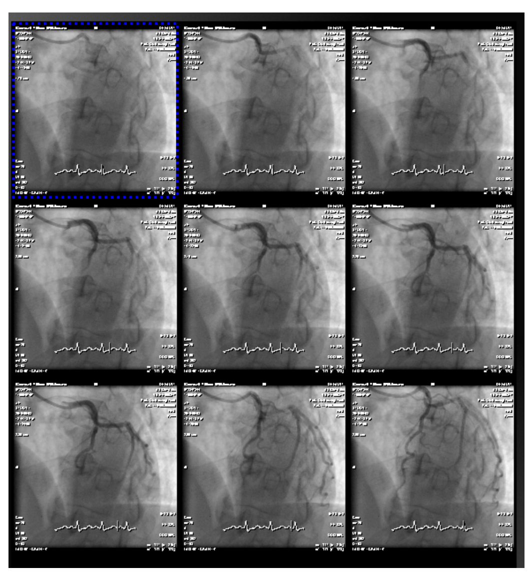

Figure 4. The frame count method for determining the contrast transport time.

2.3. Frame count measurement

The flow velocity (mm/s) was assessed by the frame count on the coronary angiography following administration of 6 ml contrast material with a 3ml/s rate by ACIST™ Injection System (BBraun).

Volumetric blood flow was calculated on the basis of the contrast material transport time from the TIMI frame count (**t**) (Figure 4), and contrast transport distance (during one heart cycle) (**d**) from the 3D reconstruction using the following equation (Figure 5):

$\mathbf{Q = A_{norm} \times d / t}$ where A_{norm} is the reference area

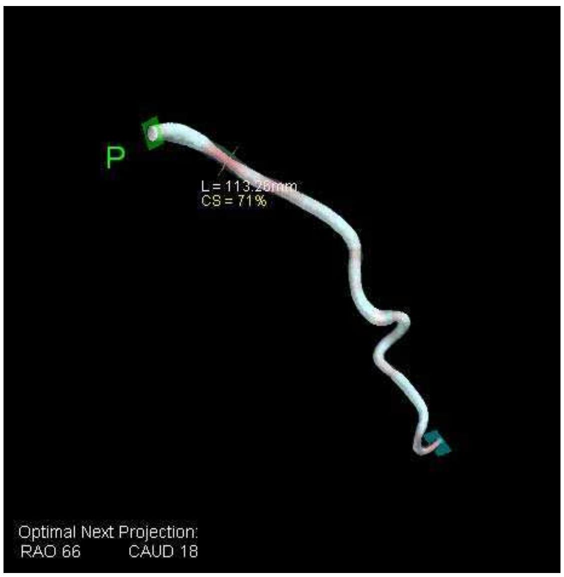

Figure 5. 3D reconstruction of the whole vessel for measuring the contrast transport distance.

2.4. Calculation of pressure gradients

Pressure gradients were calculated on the basis of the fluid dynamic equations:

$$\Delta P_F = 8\pi\eta L \;/\; A^2_{sten} \;\times\; Q$$
$$\Delta P_S = \rho / 2 \times (1/ A^2_{sten} - 1/ A^2_{norm}) \times Q^2$$
$$\Sigma\Delta P = \Delta P_F + \Delta P_S$$

Where :
ρ – blood density: 1055 g/l
η – blood viscosity: 3.5 cP
L – stenosis length (mm)
A – normal et stenotic cross-sectional area (mm²)
Q – blood flow (ml/s)

MedCalc software was used for statistical analysis when comparing the results of FFR and plaque volume. P-values less than 0.05 were considered statistically significant. The correlations between the calculated and measured rest pressure ratio as well as the FFR values were assessed by linear regression analysis.

3. Results

Regression analysis demonstrated strongly significant relationship between the calculated resting and hyperemic pressure ratio (FFR) (twofold flow was assumed during vasodilatation) ($r=0.66$ and 0.88; $p=0.007$ and $p<0{,}001$, respectively).

From the 3D parameters only the AS and the PV showed significant correlation with the FFR ($r=0.62$ and 0.71; $p=0.013$ and 0.003, respectively).

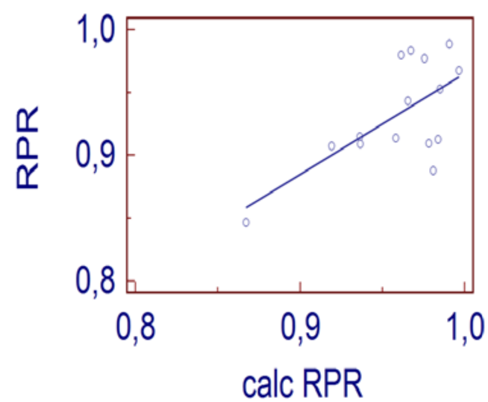

Figure 6. Correlation of the calculated rest pressure ratio (calc RPR) with the measured RPR ($r = 0.66$; $p=0.007$).

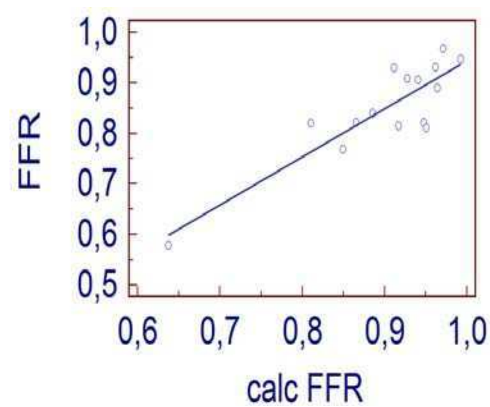

Figure 7. Correlation of the calculated FFR with the measured FFR ($r=0.88$; $p< 0.001$).

4. Discussion

2D coronary angiography currently is the gold standard for assessing coronary artery disease (CAD). The functional severity of intermediate stenoses (40-70% narrowing in diameter), however, cannot be evaluated by this method, therefore clinical decision-making requires an additional diagnostic procedure. For the functional assessment the determination of the fractional flow reserve (FFR) by pressure sensor guidewire has become the gold standard, because FFR has showed good correlation with the degree of myocardial ischemia and coronary events. FFR is calculated as Pa/Pd, and a value <0.75 implies significance, with values between 0.75 and 0.80 being considered a “gray zone.” In studies this value strongly correlates with noninvasive ischemia, and post-intervention resolution of abnormal FFR also correlates with resolution of ischemia. Furthermore, the DEFER and the FAME studies demonstrated that interventions on intermediate lesions with FFR of ≥0.75-0.80 can be safely deferred with an annual risk of cardiac death or myocardial infarction <1% [4-6].

Taking into account the fact that the 3D analysis of a coronary stenosis can provide more precise data determining the pressure drop, 3D approach can be a more accurate predictor of functional significance than 2D-QCA .

Our present results confirmed our previous finding about the 3D-QCA plaque volume [7]. We found that beside the 3D cross sectional stenosis, the calculated “functional” PV characterizing the entire lesion is also an important predictor of the flow consequence of the stenosis. 3D angiographically detected PV is defined from the extrapolated ”normal” target vessel volume. This 3D-QCA derived PV is usually lower than the real plaque burden that can be detected by IVUS, however, functionally it can have a more important flow effect than that detected by other modalities, involving also the non-obstructive part of the plaque in the vessel wall.

Few studies have compared 3D-QCA and FFR in intermediate coronary stenoses.

Saad et al. reported better accuracy of 3D-QCA than 2D-QCA in predicting FFR< 0.75 [8]. They found significant correlation between FFR and cross-sectional area percentage stenosis (AS) in 3D. Compared with FFR, the 3D AS of 57% had the highest sensitivity and specificity for determining the significance of the lesion.

Yong et al. compared the calculated parameters of 3D and 2D QCA, and their prediction of reduced fractional flow reserve [9]. Of all measurements of lesion severity obtained by 3D-QCA, minimal lumen area (MLA) best correlated with FFR. 3D-QCA showed a non-significant trend towards more accurate prediction of FFR than 2D-QCA. They concluded that 3D-QCA may assist in the evaluation of coronary lesions of intermediate severity.

Our results showed, that in case of good visualization of intermediate coronary artery stenosis, the calculation of pressure gradients by fluid dynamic equations using 3D angiography and frame count data can provide adequate functional assessment of the lesion.

References

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